

GOATS 2005
Integrated, Adaptive Autonomous Acoustic Sensing Systems

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LONG-TERM GOALS

To develop net-centric, autonomous underwater vehicle sensing concepts for littoral MCM and ASW, exploring collaborative and environmentally adaptive, bi- and multi-static, passive and active sonar configurations for concurrent detection, classification and localization of proud and buried targets.

OBJECTIVES

The objective of the continuing GOATS interdisciplinary research program is to develop, implement and demonstrate real-time, onboard integrated acoustic sensing, signal processing and platform control algorithms for adaptive, collaborative, multiplatform REA, MCM, and ASW in unknown and unmapped littoral environments with uncertain navigation and communication infrastructure.

A principal GOATS objective the development of a nested, distributed command and control architecture that enables individual network nodes of clusters of nodes to complete the mission objectives, including target detection, classification, localization and tracking (DCLT), fully autonomously with no or limited communication with the network operators. The need for such a nested, autonomous communication, command and control architecture has become clear from the series of experiments carried out in the past under GOATS. Thus, the experiments, most recently MB'06, have shown that acoustic communication cannot be relied upon for more traditional,

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centralized network control due to inherent, physics-driven limitations in regard to bandwidth, and equally important, in terms of its inherent latency and intermittency.

APPROACH

The GOATS (Generic Ocean Array Technology Sonar) research program is a highly interdisciplinary effort, involving experiments, theory and model development in advanced acoustics, signal processing, and robotics. The center-piece of the research effort has been a series of Joint Research Projects (JRP) with SACLANTCEN. The joint effort was initiated with the GOATS' 98 pilot experiment [1] and continued with the GOATS' 2000 and BP02/MASAI02 experiments. Currently the collaboration is being continued under two NURC JRPs – one on hybrid target scattering modeling, and one on Focused Acoustic Fields (FAF), which constituted part of the joint experiments in 2004-05. A new JRP on littoral surveillance has just been approved, beginning in 2007. In addition to the field experiments involving significant resources provided by NURC, GOATS uses modeling and simulation to explore the potential of autonomous underwater vehicle networks as platforms for new sonar concepts exploring the full 3-D acoustic environment of shallow water (SW) and very shallow water (VSW).

The fundamental approach of GOATS is the development of the concept of a network of AUVs as an array of *Virtual Sensors*, based on fully *integrated sensing, modeling and control*, reducing the inter-platform communication requirements to be consistent with the reality of shallow water acoustic communication in regard to low bit-rate, latency and intermittency. Thus, for example the past GOATS effort has demonstrated that platform motion information can be used for clutter control by providing geometric constraints to on-board detection algorithms, reducing the communication requirements to location, POD, and classification information. Conversely, on-board sensor fusion and processing can be fed back to the vehicle control system for autonomous, adaptive sampling – again with the potential for significantly enhanced POD/PFA performance.

In regards to applications to MCM, GOATS explores the use of bi-static and multi-static Synthetic Aperture created by the network, in combination with low frequency (1-10 kHz) wide-beam insonification to provide coverage, bottom penetration and location resolution for concurrent detection, localization and classification of proud and buried targets in SW and VSW. The signal processing effort is therefore centered around generalizing SAS processing to bi-static and multi-static configurations, including bi-static generalizations of auto-focusing and track-before-detect (TBD) algorithms. Another issue concerns the stability and coherence of surface and seabed multiples and their potential use in advanced low-frequency SAS concepts.

More recently, the GOATS effort has transitioned towards the development of similar, autonomous network concepts for passive littoral surveillance, e.g. the Undersea Persistent Surveillance (UPS) program, under which MIT is co-leading the PLUSNet partnership which is developing a network concept of operations based on clusters of AUV and gliders, connected via acoustic communication, and intermittent RF communication with the operators through periodically surfacing gliders. As in the past GOATS effort, MIT is utilizing the open-source MOOS control mission control software originally developed and funded under GOATS. However, in contrast to past experiments where all platforms were controlled and piloted by MIT, the PLUSNet concept envisions a suite of diverse network nodes, with significant native, proprietary, software infrastructure. To take advantage of the robustness of the native control software, while at the same time retaining the flexibility in regard to sensor-driven adaptivity and collaboration, MIT, and in turn PLUSNet, has adopted a new nested control architecture, where the lower level control of the nodes, as well as the overall field control can

be performed using arbitrary third-party software, while the medium level, adaptive and collaborative control of the nodes and the clusters is performed within the MOOS software framework.

Such a nested command and control infrastructure with heterogeneous assets invariably need translation to and from a common communications protocol. In the MB'06 experiment, MIT and Bluefin AUVs were controlled using a new, so-called “back-seat driver” paradigm wherein low-level commands to the Bluefin control software were translated and conveyed by a specially designed MOOS module. Prior to MB'06, Bluefin Robotics already had a draft payload server specification intended to allow mission redirection in real-time at various levels of sophistication. One objective, then, was to take this specification and implement flexible and robust communications between MOOS and Huxley.

The mid-level, adaptive and collaborative control of the network nodes is carried out using MOOS in combination with the new multi-objective, behavior-based control framework developed within MOOS by Michael Benjamin at NUWC/MIT. The core of this architecture consists of a behavior-based control system which uses multiple objective functions to determine the appropriate course, speed, and depth of the platform at every control cycle (typically 10-20 Hz). The desired course of action is determined by computing a multi-function optimization over the objective functions using the Interval Programming Model developed by Benjamin [5] which provides a very fast optimization suitable for small vehicles.

To interface the platform control to the overall cluster and field control another MOOS process has been designed. This process, running on all nodes, including the central control node will translate higher level messages, such as DEPLOY and PROSECUTE commands to 32-byte CCL (Command and Control Language) messages which are then transmitted via an acoustic modem. On the receiving node, the same process performs the decoding and passes the command on to the MOOS node control. Similarly target contact reports generated by a node will be translated into a CCL message, which is then transmitted via acomm to field control.

The development of GOATS concepts, including PLUSNet, is based heavily on simulation, incorporating and integrating high-fidelity acoustic modeling, platform dynamics and network communication and control. In regard to the environmental acoustic modeling, MIT continues to develop the OASES-3d modeling framework for target scattering and reverberation in shallow ocean waveguides. As has been the case for the autonomous command and control, recent emphasis has been towards the simulation of passive DCLT by the PLUSnet network. As was previously the case for the MCM effort, the approach has been to develop a complete system simulation capability, where complex adaptive and collaborative sensing missions can be simulated using state-of-the-art, high-fidelity acoustic models for generating synthetic sensor signals in real time. As in the past, this has been achieved by linking the real-time MOOS simulator with the SEALAB acoustic simulation framework, which in ‘real-time’ generates element-level timeseries using Green’s functions using legacy environmental acoustic models such as OASES, CSNAP, and RAM. This new unique simulation environment allows for full simulation of adaptive DCLT missions for the MIT/Bluefin Macrura AUV towing a vector sensor array, incorporating correlated and directional ambient noise, and signals generated by moving surface ships and targets

WORK COMPLETED

Nested, Distributed Autonomous Communication, Command and Control Architecture

A significant part of the FY06 effort has been aimed towards the development of the new nested autonomous communication, command and control framework centered around MOOS, and it's demonstration in MB'06.

Backseat Driver Paradigm

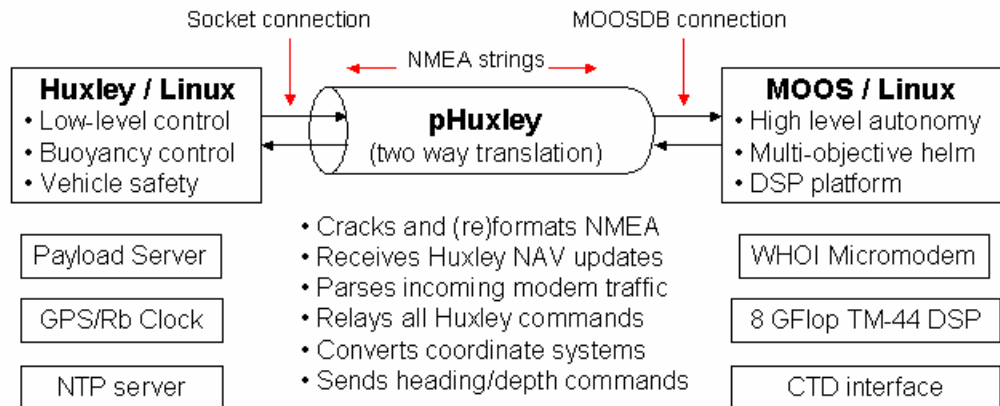


Figure 1 Backseat driver paradigm. Sensing, communication, modeling, and mid-level, adaptive control performed in payload computer running MOOS, while lower-level cplatform control, navigation and safety is handled by main vehicle computer running native Bluefin Huxley control software.

The Bluefin Robotics payload server specification is based on a set of NMEA sentences – some conveying navigation and vehicle state information from Huxley to MOOS and others providing command and communication requests from MOOS to Huxley. NMEA sentences are passed between Huxley and the MOOS interface process, dubbed pHuxley, via a 100Base-T vehicle network. Communication is implemented over a standard socket layer, designed to re-initiate in the event of transient failures. Whereas the entire MOOS system is built on socket-based interprocess communication (IPC), pHuxley uses a separate, simplified socket class, intended to provide minimal functionality with maximum robustness. Approximately half of the code in pHuxley is concerned with taking the navigation updates from Huxley, which occur at several Hertz, and publishing extracted state variables into the local MOOS data base (MOOSDB) using MOOS naming conventions. Not all Huxley variables can be published directly in this way, however, as – for example – the Bluefin payload server specification deals exclusively in geographic coordinates, whereas MOOS operates internally on local grid coordinates. The pHuxley module handles such coordinate and unit conversions in both directions such that both systems have equivalent representations of the vehicle state.

To simplify the vehicle control interface between MOOS and Huxley, only one NMEA sentence type is issued by pHuxley. This sentence contains the current desired heading, depth and speed of the vehicle, as published by the MOOS IvP helm module. Blanks in any of the above three parameter fields are taken to indicate a continuation of the previously commanded value. Following a

configurable period of inactivity from MOOS, the Bluefin Huxley control system is programmed to abort the currently active mission and surface – by emergency means if necessary.

Separating low-level vehicle control from high-level autonomy in this way has several advantages, chiefly in relegating tasks such as heading and depth control, which are highly vehicle specific, to the vehicle manufacturer. In particular, issues of PID controller tuning and emergency response do not concern the MOOS infrastructure, nor any other higher level of control. Vehicle actuator control, therefore, is at the lowest level of what is a hierarchy of nested control levels.

Behavior-based Control – IvP-Helm

A significant effort was made in FY 06 to develop the autonomy architecture needed to provide adaptive and cooperative behavior for the sensor platforms (primarily AUVs and autonomous surface craft) carrying out the MCM, ASW, and REA missions. The core of this architecture consists of a behavior-based control system which uses multiple objective functions to determine the appropriate course, speed, and depth of the platform at every control cycle (typically 10-20 Hz). The kernel of the platform control is the Interval programming helm (IvP-Helm) implemented as a MOOS process performing and coordinating all platform sensing, decision and actions. The desired course of action is determined by computing a multi-function optimization over the objective functions using the Interval Programming Model developed by Benjamin [5] which provides a very fast optimization suitable for small vehicles.

The behavior-based control architecture was further augmented by the development of a “logical” targeting sensor designed to output feature-level data suitable for use by the behaviors in the control system. Consisting of the physical sensor and associated processing algorithms, this architecture separates the determination of what is being sensed away from the determination of what to do about it. A number of adaptive behaviors were developed for the ASW and REA missions and tested locally in the Charles river and subsequently in Monterey Bay in conjunction with the PLUSNet MB '06 experiment. Results are further described below.

Network and Field Control - NAFCON

At the highest level of the control hierarchy is the pNAFCON module, which also forms part of the MOOS process community running on the vehicle payload. This module deals either directly and indirectly with communication between the vehicle and Network and Field Control (NAFCON). The pNAFCON module incorporates a vehicle-specific interpretation of the PLUSNet IDD and interfaces directly to the MOOS IvP helm via MISSION_CONTROL strings published in the MOOSDB. The autonomy of the MOOS helm, therefore, exists within an overall nested control architecture, at times being free to act independently and at other times being more tightly constrained, depending on which mode has been selected by pNAFCON as a result of NAFCON communications traffic.

MIT Acoustic Sensing Network Simulator

MOOS-SEALAB HiFi Acoustic Simulator

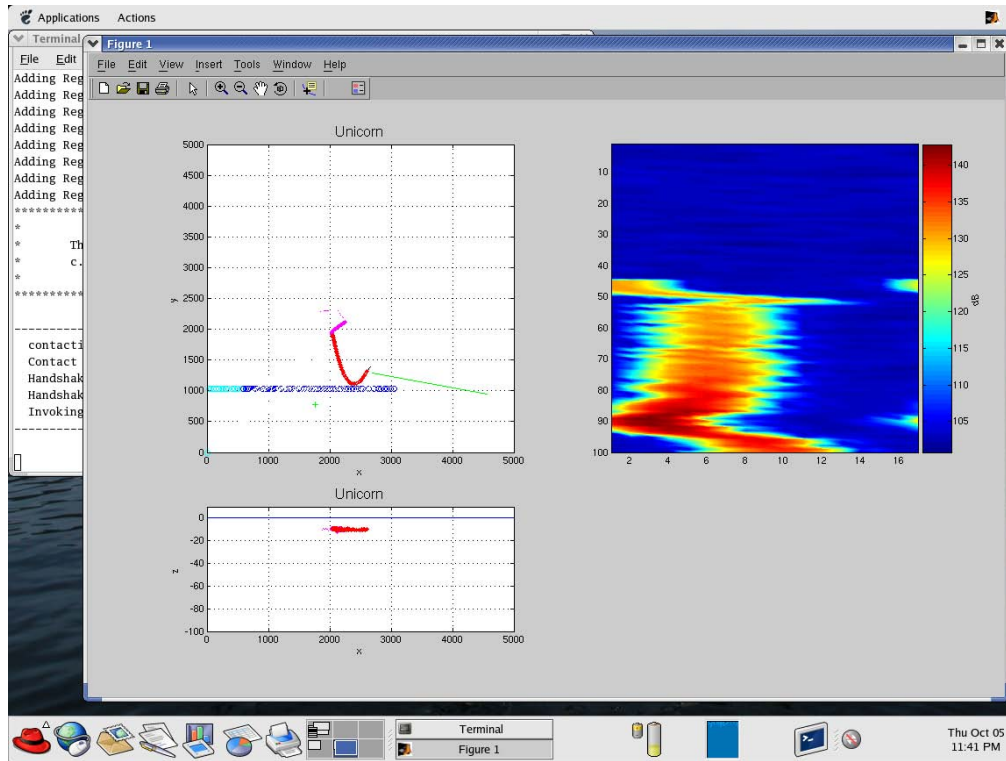


Figure 2 MOOS-SEALAB autonomous DCLT simulator. Adaptive vehicle track shown in red in upper left frame. The green line indicates the current bearing track, with the ‘true’ target track indicated in blue. The right frame shows BTR generated by onboard, real-time beamforming using simulated element-level time-series including signal and noise.

The development of the robust and efficient processing algorithms and autonomous, adaptive and collaborative behaviors at the core of GOATS, it crucial to the effective use of at-sea time and resources, to have available a comprehensive simulation environment. With its modular structure, composed of individual processes communicating through a central database, MOOS is inherently capable of being run in simulation mode in a configuration that is arbitrarily close to the configuration running the actual missions. Thus, the simulation can be performed on the actual vehicle computer or a separate laptop or desktop, with some of the hardware in-the-loop, such as acoustic modems. Also, the simulator has a Matlab interface, which allows new processing algorithms and behaviors to be developed interactively in Matlab, and then later compiled into true, real-time MOOS processes. To support the development of the new net-centric sensing concepts MIT has developed such a simulation framework, which has been used extensively for the adaptive MCM behaviors developed in the past [2]. More recently it has been adapted to the passive littoral surveillance problem and used extensively in the PLUSNet project. Some of the new features include a full dynamic model of the vector-sensor towed array (VSA), coupled with the real-time acoustic simulator SEALAB (courtesy of VASA Associates), which provides element-level time-series including signals and noise, generated using state-of-the-art wave-theory models such as OASES, CSNAP and RAM. This new capability is used

extensively for developing the real-time VSA processing, and the adaptive behaviors. Figure 2 shows a screen-shot of the Matlab visualization program, showing the adaptive track of a simulated target prosecute behavior, with the simulated BTR on the right.

3D Coupled Mode Modeling

To enable high-fidelity modeling of 3D propagation in shallow water with complex bathymetry, MIT has developed a new coupled mode framework, based on the NURC CSNAP legacy model [4], combined with an exact Fourier decomposition of the azimuthal dependence of the scattered field. Using the classical principle expressing the total field as a superposition of the incident field and the scattered field, the field around a circular seamount is represented very efficiently by the unperturbed 2D field produced by the source in the absence of the seamount. For three-dimensional problems, the new model can be applied to solve problems involving oblique interaction, including back-scatter, with linear seabed features such as ridges, and propagation around conical seamounts.

RESULTS

Autonomy Architecture

The new autonomy architecture was first tested in a series of tracking experiments using autonomous surface craft with simulated bearing sensors on the Charles River [6]. In the first experiment, a moving target (another autonomous surface craft) was tracked by a single sensor vehicle using only target bearings. In the second experiment, a similar target was tracked using two networked sensor platforms which fused two simultaneous bearings from two sensor platforms to estimate the target track. Representative results from each experiment are shown. As can be seen in Fig. 3 and 4, there is a significant advantage to using multiple, collaborating sensor platforms.

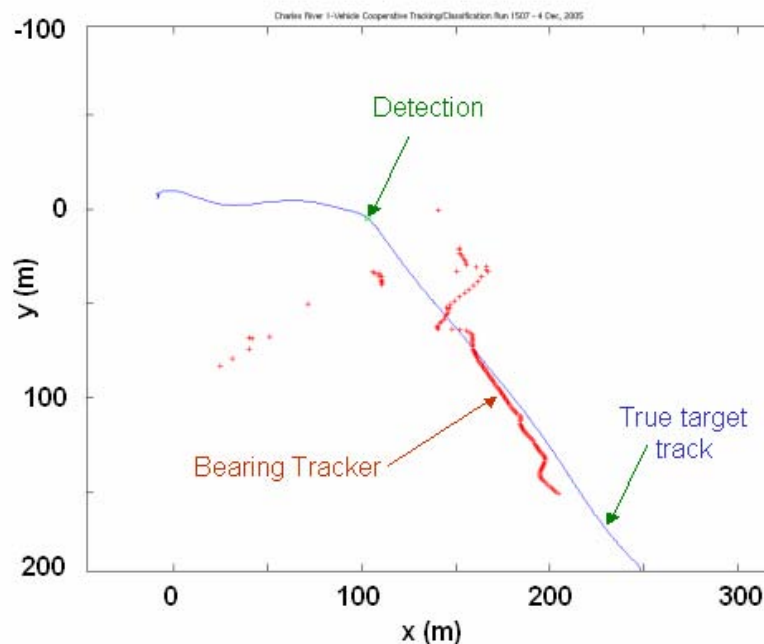


Figure 3 – Target track estimation using a single sensor platform.

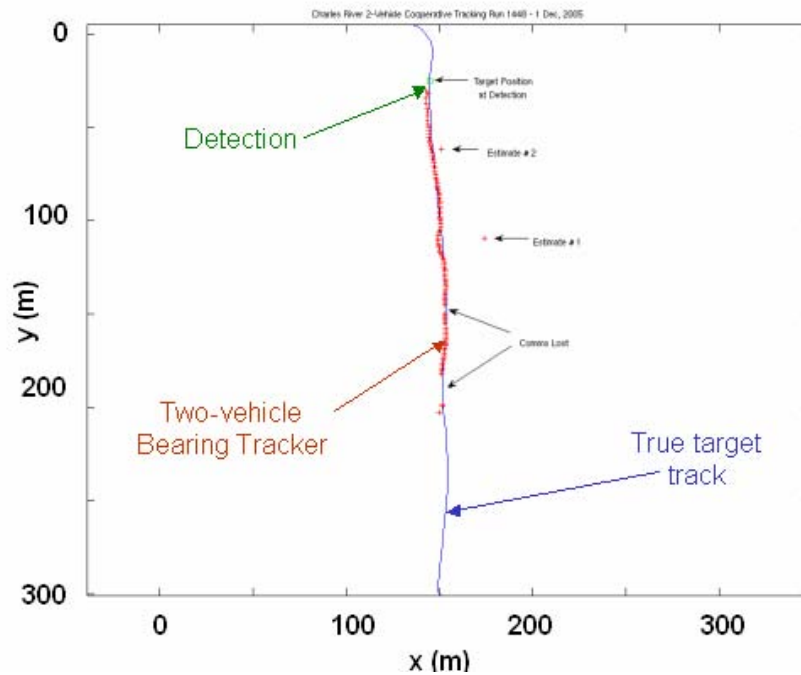


Figure 4 - Target track estimation using two networked sensor platforms.

The autonomy architecture was further tested in Monterey Bay in a number of adaptive deployment and target prosecute missions. Figure 5 shows an example of a deployment into a hexagonal loiter pattern, followed by a redeployment 500 m west, initiated by an acoustic communication CCL command from the NAFCON field control. In addition, a series of behaviors were developed and tested for adaptively assessing environmental features critical to the acoustic environment, such as internal waves and fronts.

Re-deploy Command Response

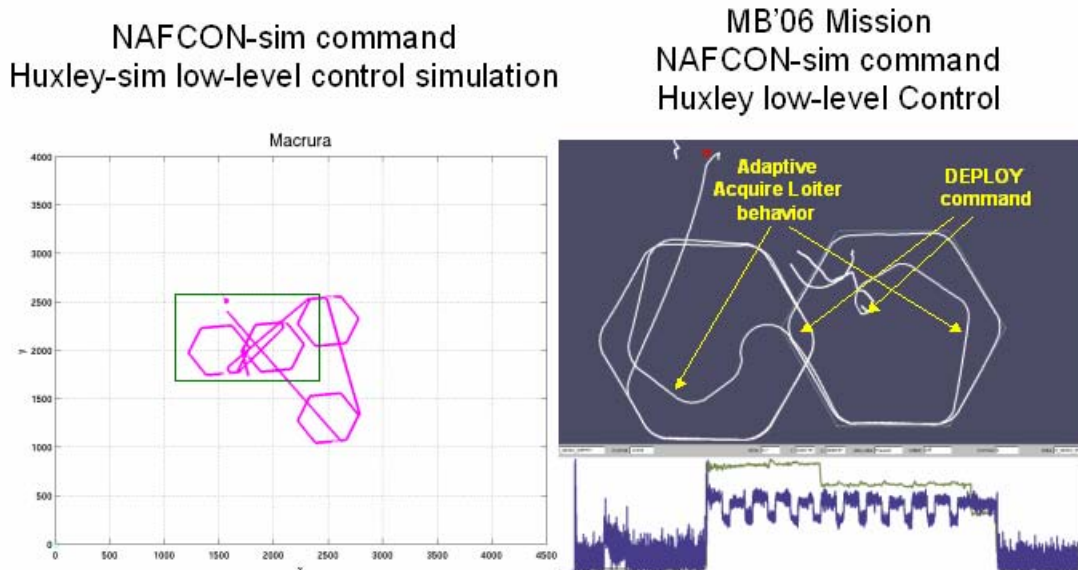


Figure 5. MB06 DEPLOY and REDEPLOY missions executed using MOOS-IvP command and control. The left frame shows a simulation of successive re-deployments into hexagonal loitering patterns. The frame to the right shows the navigation record for the actual mission. Note the smooth turns, which were executed using a dedicated turn-limit behavior, designed to avoid twisting the towed array cable. The behavior smoothly transitions from one loiter pattern to the other. The lower right frame shows the depth in green, and the speed in blue. Note the periodic speed behavior, which was designed to improve acoustic communication reception on the vehicle. Status messages from the vehicle were used to alert the NAFCON field control about upcoming low-speed communication windows.

Acoustic Modeling and Simulation

3D Acoustic Scattering from a Conical Seamount

The new 3D seamount interaction model has been exercised extensively to analyse the significance of 3D effects. This analysis is currently focusing on the Kermit Seamount for analysis of the NPAL experimental data. However, for computational reasons, the analysis was first performed for a scaled down, shallow water seamount problem. The geometry is shown in Fig.6. The water depth is 250 m, the height of the seamount is 100 m, the source frequency 40 Hz, the source range and depth 800 m and 100 m, respectively. The left frame of Fig.7 shows the comparison of 3D and 2D models for propagation over the top of the seamount, where the 3D effect is minimal, while the frame to the right shows the transmission loss along a direction cutting the seamount halfway down the side where the 3D effect is significant. Fig.8 shows contours of the transmission loss in a horizontal plane at depth 100 m. Fig.9 shows transmission loss in the vertical plane passing over the top of the seamount.

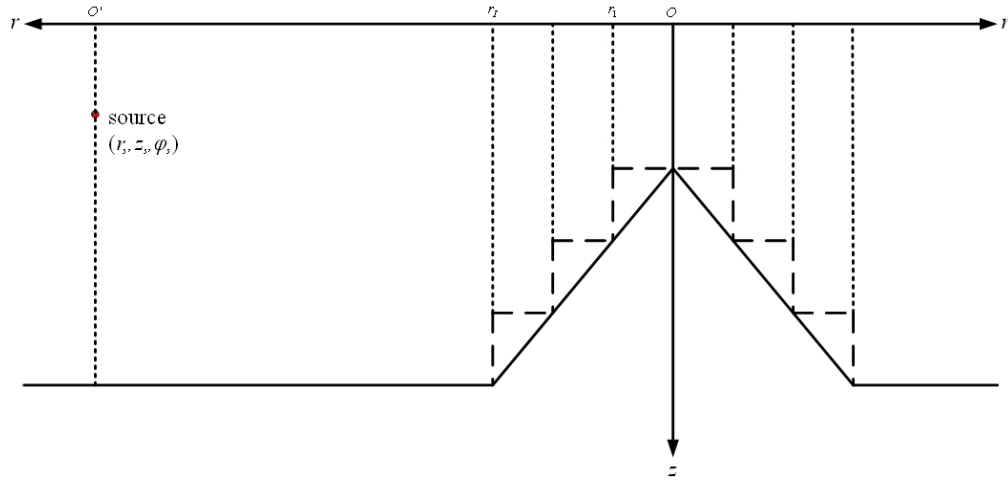


Fig.5 Shallow water wave-guide with a conical seamount and a point source.

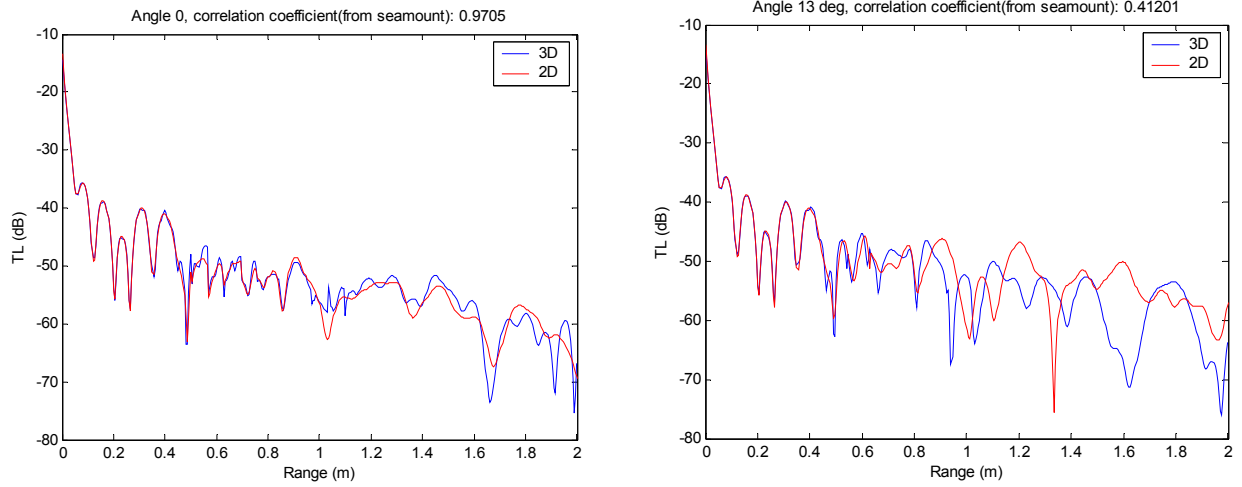


Fig.6 Comparison of 3D and 2D models for four different propagation directions across conical seamount. The 3D effect is relatively insignificant across top of seamount (left), while the 3D effect is strong for propagation along direction crossing the seamount approximately halfway down the side (right).

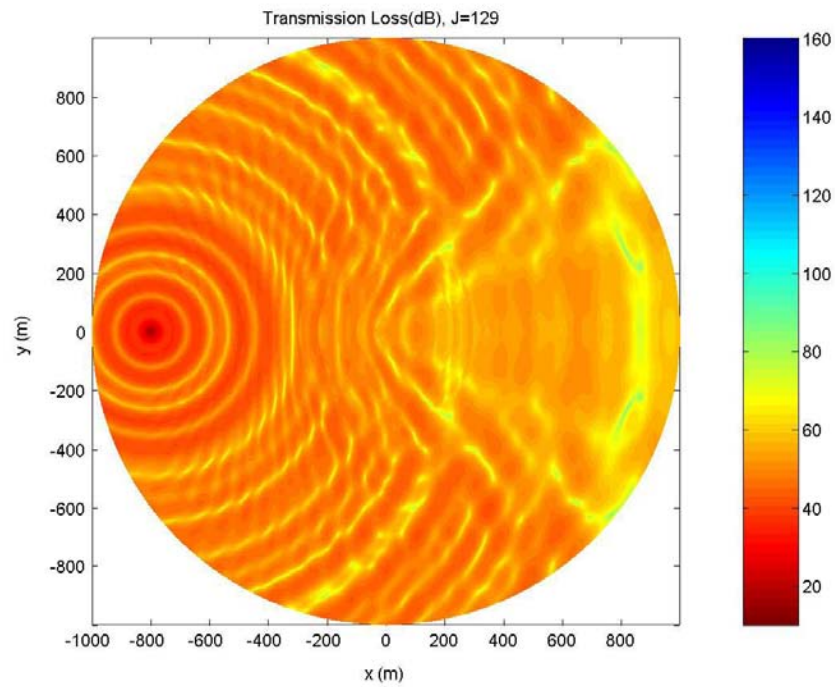


Fig.7 Transmission at depth 100 m.

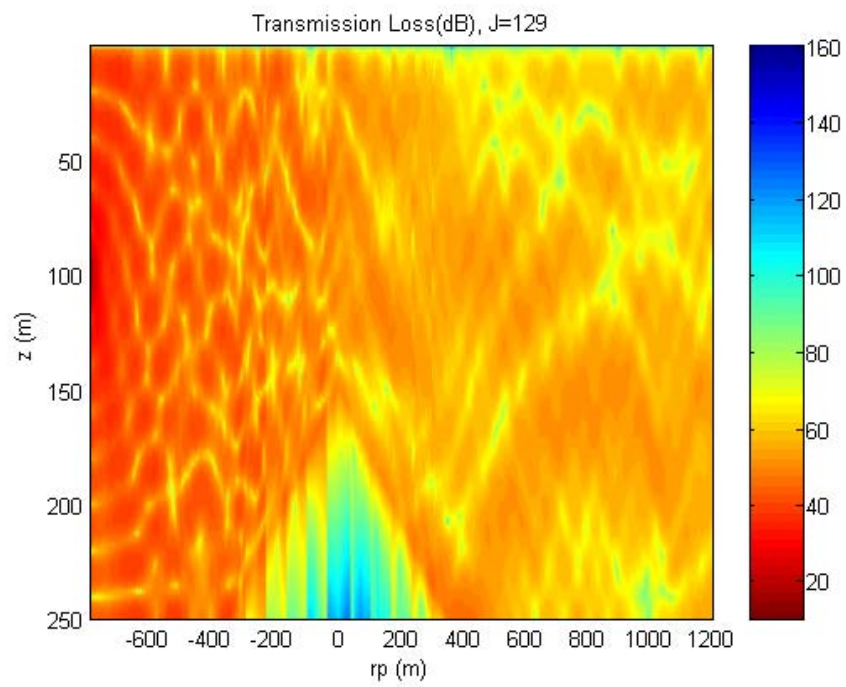


Fig.8 Transmission at azimuthal angle $\varphi' = 0$.

IMPACT/APPLICATIONS

The long-term impact of this effort is the development of new sonar concepts for MCM and ASW, which take optimum advantage of the mobility, autonomy and adaptiveness of an autonomous, cooperating vehicle network. For example, bi- and multi-static, low-frequency sonar configurations are being explored for completely or partially proud or buried mines in shallow water, with the traditional high-resolution acoustic imaging being replaced by a 3-D acoustic field characterization as a combined detection and classification paradigm, exploring spatial and temporal characteristics which uniquely define the target and the reverberation environment. Similarly, platform mobility and collaboration is being explored for enhancing DCLT performance of littoral surveillance networks such as PLUSNet.

TRANSITIONS

The progress made in autonomous, multi-AUV, net-centric control, navigation, communication, and collaborative sensing is being transitioned into the ASAP-MURI and the new Undersea Persistent Surveillance (UPS) PLUSNet efforts, both of which have MIT as partners, with field demonstrations of autonomous adaptive sensing and control in Monterey Bay in FY06. PI Schmidt is Co-lead PI on PLUSNet.

Particular emphasis in FY05 was aimed at transitioning the active MCM sonar concepts developed and demonstrated under GOATS, to the autonomous, littoral ASW problem, currently being addressed in the ONR Undersea Persistent Surveillance (UPS) program. The FAF'05 experiment July 11-29, 2005, carried out jointly with NURC, was aimed at adapting the integrated sensing, modeling and control paradigm to the passive ASW DCL problem. The DCLN sonar developed and demonstrated under GOATS was modified to continuously stream data from the nose arrays on the MIT BF21 vehicles, and real-time DCL algorithms and adaptive vehicle control, developed for the MCM problems were modified and successfully demonstrated for real-time, autonomous detection, localization and tracking of a moving source.

The results of the multi-vehicle navigation, communication and cooperative behavior is being transitioned into the Autonomous Operations Future Naval Capabilities (AOFNC) project *Demonstration of Undersea, Autonomous Operation Capabilities and related Technology Development*. John Leonard is the MIT PI of this joint project with Bluefin Robotics and the Naval Undersea Warfare Center (NUWC).

The OASES and CSNAP environmental acoustic modeling codes are used extensively in this work and continue to be maintained, expanded and made available to the community. It is continuously being exported or downloaded from the OASES web site, and used extensively by the community as a reference model for ocean seismo acoustics in general.

(<http://acoustics.mit.edu/arctic0/henrik/www/oases.html>) Among the new transitions to applied Navy programs, the OASES and CSNAP framework is being used extensively by several contractors such including Lockheed-Martin, BBN, Northrop-Grumman, and SAIC., and Navy laboratories, including NUWC, NURC, CSS, and NRL.

RELATED PROJECTS

This effort has constituted part of the US component of the GOATS'2000 Joint Research Project (JRP) with the SACLANT Undersea Research Centre, and is currently collaborating with NURC under the Hybrid Target Modeling and Focused Acoustic Field (FAF) Joint Research Projects (JRP). The MIT GOATS effort has been funded jointly by ONR codes 321OA (Livingston), 321OE (Swan, Curtin), and 321TS (Johnson/Loeffler/Commander).

The GOATS program developed out of the ONR Autonomous Ocean Sampling Network (AOSN) initiative completed in FY00, and is strongly related to the continuing AOSN effort. GOATS is also directly related to the Shallow Water Autonomous Mine Sensing Initiative (SWAMSI), initiated in FY04, and currently continuing, of which MIT is a partner.

The adaptive command and control architecture and acoustic modeling capabilities developed under GOATS are being applied in several other related programs MIT is partnering in, including the AREA (Adaptive Rapid Environmental Assessment) component of the now completed ONR "Capturing Uncertainty" DRI, aimed at mitigating the effect of sonar performance uncertainty associated with environmental uncertainty by adaptively deploying environmental assessment resources. The cooperative AUV behavior progress together with the AREA concept is being currently transitioned into the ASAP MURI and the Undersea Persistent Surveillance (UPS) program, with experimental demonstrations in Monterey Bay in MB06.

The OASES modeling framework, which is being maintained, upgraded, and distributed to the community under this award, has been used intensively in all the related programs MIT is participating in. The new 3D model of propagation over seamounts is being transitioned and applied to the analysis of the experimental results obtained at Kermit seamount under the NPAL program.

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HONORS/AWARDS/PRIZES

Prof. Henrik Schmidt was awarded the *Pioneers of Underwater Acoustics Medal* of the Acoustical Society of America, presented at the 150th Meeting of the Acoustical Society of America, Oct. 17-21, 2005 in Minneapolis, MN.